Chapter 5
Summary of Coalbed Methane Basin Descriptions

An extensive literature review was conducted to collect information regarding the major coal basins in the United States. Eleven major coal basins were identified in the United States and are presented in this chapter (Figure 5-1). The specific goals of this survey were:

- To determine the physical relationship between the coalbeds and the USDWs;
- To confirm whether hydraulic fracturing is used to stimulate coalbed methane wells in production basins;
- To collect information on the fluids used to create the fractures, and where possible; and
- To determine if the potential for contaminants to enter a USDW exists.

This information is necessary to evaluate whether hydraulic fracturing is practiced within a basin and the types of fluids used in the fracturing process. More importantly, this information establishes whether the coal formations lie within a USDW, creating the potential for impacts from the injection of fracturing fluid. Descriptions for each of the eleven major basins are presented in this chapter and in Table 5-1. Complete basin descriptions are provided in Attachments 1 through 11 of this report. In some cases, very little information was uncovered by the EPA regarding certain topics in certain basins. Every effort was made to present all of the information collected regarding the topics presented in the basin summaries.

5.1 The San Juan Basin

The San Juan basin covers an area of about 7,500 square miles across the Colorado-New Mexico state line in the Four Corner region (Figure 5-1). It measures roughly 100 miles long in the north-south direction and 90 miles wide. The Continental Divide trends north-south along the east side of the basin.

The major coal-bearing unit in the San Juan basin is known as the Fruitland formation. Coalbed methane production occurs primarily in coals of the Fruitland formation, but some coalbed methane is trapped within the underlying and adjacent Pictured Cliffs sandstone, and many wells are completed in both zones. The coals of the Fruitland formation are very thick compared to coalbeds in eastern basins: the thickest coals range from 20 to over 40 feet thick. Total net thickness of all coalbeds ranges from 20 to over 80 feet throughout the San Juan basin, compared to five to 15 feet in eastern basins.

Coalbed methane wells in the San Juan basin range from 550 to 4,000 feet in depth, and about 2,550 wells are currently operating (CO Oil and Gas Conservation Commission and NM Oil Conservation Division, 2001). The San Juan basin is the most productive coalbed methane basin in North America. Coalbed methane production in the San Juan basin averages about 800 thousand cubic feet per day per well (Stevens et al., 1996).

Coalbed methane production in the San Juan basin totaled over 800 billion cubic feet in 1996 (Stevens et al., 1996). This number rose to 925 billion cubic feet in 2000 (GTI, 2002).

The majority of coalbed methane development and hydraulic fracturing in the northern portion of the San Juan basin take place within a USDW. The waters in parts of the Fruitland formation usually contain less than 10,000 mg/L TDS. In the northern half of the formation, most waters contain less than 3,000 mg/L, and wells near the outcrop produce water that contains less than 500 mg/L.

Fracturing fluids used in the San Juan include hydrochloric acid, slick water (water mixed with solvent), linear and crosslinked gels, and since 1992, nitrogen-based or carbon dioxide-based foams (Harper et al., 1985; Jeu et al., 1988; Holditch et al., 1988; Palmer et al., 1993; Choate et al., 1993). Data are not readily available concerning fracture growth and height within the Fruitland Formation.

5.2 The Black Warrior Basin

The Black Warrior Basin is the southernmost of the three basins comprising the Appalachian Coal Region of the eastern United States. The basin covers an area of about 23,000 square miles in Alabama and Mississippi, and is approximately 230 miles long from west to east and approximately 188 miles long from north to south (Figure 5-1). Basin coalbed methane production is limited to the bituminous coalfields of west-central Alabama, primarily in Jefferson and Tuscaloosa counties.

Coalbed methane production in the Black Warrior is confined to the Pennsylvanian aged Pottsville formation. The ancient coastline of prehistoric Alabama was characterized by eight to ten "coal deposition cycles" of sea level rising and lowering. Each of these ten geologic "coal deposition cycles" features mudstone at the base of the cycle (deeper water) and coalbeds at the top (emergence). Most coalbed methane wells tap the Black Creek/Mary Lee/Pratt cycles, using wells from 350 to 2,500 feet deep (Holditch, 1990).

Coalbed methane production in the Black Warrior basin is among the highest in the United States. In 1996, about 5,000 coalbed methane wells had been permitted in Alabama. In 2000, this number was reduced to nearly 4,000 wells (GTI, 2002). Historically, typical production has averaged about 300 thousand cubic feet per day per well (Hewitt, 1984; McFall et al., 1986; Schraufnagel, 1993). Pashin and Hinkle (1997) estimate that the Black Warrior Basin produced roughly 100 billion cubic feet of gas annually, which is about 20 percent of state gas production from all methods. Nineteen of the twenty-one coalbed methane fields (constituting 90 percent of coalbed methane production) operating in the state are located within the Black Warrior coal basin (Pashin and Hinkle, 1997). Total coalbed methane production stood at 112 billion cubic feet in 2000 (GTI, 2002).

The waters of the Pottsville formation contain less than 10,000 mg/L TDS, which defines the formation as a USDW. Most waters contain less than 3,000 mg/L, and a large proportion contain less than 500 mg/L (Pashin et al., 1991; Pashin and Hinkle, 1997).

The most common component of fracturing fluid is plain water. In the Pottsville formation, the lack of a significant vertical barrier provides fracture height growth that can approach 600 feet (Ely et al., 1990; Zuber et al., 1990). Early literature indicated that most of the wells in production in the early 1990s have been hydraulically fractured an average of two to six times to achieve acceptable production rates (Holditch et al., 1988; Holditch, 1990; Palmer et al., 1993; Palmer et al., 1993a).

5.3 The Piceance Basin

The Piceance Coal basin is wholly contained within the state of Colorado, and is located in the northwest corner of the state (Figure 5-1). The coalbed methane reservoirs are found in the Upper Cretaceous Mesaverde Group, which covers about 7,225 square miles of the basin.

The Mesaverde Group ranges in thickness from about 2,000 feet on the west to about 4,600 feet on the east side of the basin (Johnson, 1989). The depth to the methane-bearing Cameo-Wheeler-Fairfield coal zone is about 6,000 feet. Two-thirds of the coalbed methane occurs in coals deeper than 5,000 feet, and the Piceance Basin is one of the deepest coalbed methane areas in the United States (Quarterly Review, August 1993).

The depth of the coals in the Piceance basin inhibits permeability, making it difficult to extract the coalbed methane. This, in turn, has slowed coalbed methane development in the basin. However, it is estimated that 80 to 136 trillion cubic feet of coalbed methane are contained within the Cameo-Wheeler-Fairfield coal zone of the basin (Tyler et al., 1998). Total coalbed methane production was 1.2 billion cubic feet in 2000 (GTI, 2002).

The Piceance Basin contains both alluvial and bedrock aquifers. Unconsolidated alluvial aquifers (narrow and thin deposits of sand and gravel formed primarily along stream courses) are the most productive aquifers in the Piceance Basin. The bedrock aquifers are known as the upper and lower Piceance Basin aquifer systems. The upper aquifer system is about 700 feet thick and the lower aquifer system is about 900 feet thick. Water at depth in the Piceance Basin appears to be of poor quality, minimizing its chance of being designated as a USDW. A composite water quality sample taken from 4,637 to 5,430 feet deep within the Cameo coal zone exhibited a TDS level of 15,500 mg/L (Graham, CDWR, personal communication 2001).

Hydraulic fracturing is practiced in this basin. The fluids used for fracturing vary from water with sand proppant to gelled water and sand. It was shown that, in some cases, hydraulic stimulations created short (100-foot), multiple fractures around the wells (Quarterly Review, August 1993).

Research suggests that exploration may target areas where ground water circulation may enhance gas accumulation in the coal and associated sandstones (Tyler et al., 1998). Under these exploration and development conditions, it might be possible that if a USDW were located in shallower Cretaceous rocks near the margins of the basin, it could be affected by hydraulic fracturing. However, the likelihood of the presence of a USDW in these rocks is remote. The depth to methane-bearing coals (about 6,000 feet) seems to indicate that, in the Piceance Basin, the chances of contaminating any overlying, shallower USDWs (no deeper than about 1,000 - 2,000 feet) from hydraulic fracturing techniques are minimal. The coalbed methane producing Cameo zone and the deepest known aquifer, the lower bedrock aquifer, have a stratigraphic separation of over 6,000 feet, making the potential for cross contamination exceedingly small.

5.4 The Uinta Basin

The Uinta Coal Basin is mostly contained within the State of Utah, with a very small portion of the basin located in northwestern Colorado (Figure 5-1). The basin covers an area of approximately 14,450 square miles (Quarterly Review, August 1993). The Uinta Basin is stratigraphically continuous with the Piceance Basin of Colorado, but is structurally separated from it by the Douglas Creek Arch, an uplift near the state line between Utah and Colorado.

Coal seams occur in the Cretaceous Mancos Shale and the Upper Cretaceous Mesaverde Group (Quarterly Review, 1993). Two major formations targeted for coalbed methane exploration are the Mancos Shale's Ferron Coals, which are the coals most targeted (approximately 90% of the time) for exploration (Petzet, 1996), and the Mesaverde Group's Blackhawk Formation, which contains about 14 coal zones (Petzet, 1996). The Ferron Coals are interbedded with sandstone and form a wedge of clastic sediment 150 to 750 feet thick. Depths to coal in the Ferron Sandstone range from 1,000 to over 7,000 feet below ground surface (Garrison et al., 1997). The Blackhawk Formation consists of coal seams interbedded with sandstone and a combination of shale and siltstone. Coals tapped in the Blackhawk Formation are located 4,200 to 4,400 feet below the surface (Gloyn and Sommer, 1993).

Exploration within the Uinta Basin began full-scale in the 1990s (Quarterly Review, 1993). A query of a database covering the Uinta Basin revealed that there are about 1,255 coalbed methane wells in production in the basin (Osborne, USEPA Region VIII, personal communication 2002). The coalbed methane potential of the Uinta Basin, revised by the Utah Geological Survey in the early 1990s, has been estimated to be between 8 trillion cubic feet and more than 10 trillion cubic feet (Gloyn and Sommer, 1993). Total production stood at 75.7 billion cubic feet of coalbed methane in 2000 (GTI, 2002).

The Ferron coals and the Blackhawk Formation in the Uinta basin qualify as USDWs. Waters from the Ferron Sandstone in the Drunkard's Wash Field are conflictingly reported to have TDS levels of about 13,000 mg/L and more moderate levels of TDS of about 5,000 mg/L (Gwynn, 1998; Quarterly Review, 1993). However, the higher value pertains to water samples taken from evaporation lagoons, and probably does not represent the original formation chemistry (Gwynn, 1998). Ground water from the Blackhawk Formation within the Castlegate Field contains a TDS concentration below the USDW standard of 10,000 mg/L. Published TDS levels of 5,000 mg/L in production waters from the Castlegate Field coalbeds (which are contained in the Blackhawk Formation) indicate that methane gas wells in this portion of the basin are located within a USDW.

Fracturing fluid use is documented in the literature pertaining to the Uinta basin. One company reported that they performed hydraulic fracturing stimulations using cross-linked borate gel with 250,000 lbs. of proppant (Quarterly Review, 1993). Others report that they fractured wells with a low-residue gel fracturing fluids and foams (Quarterly Review, 1993).

It is unlikely that contamination is occurring in USDWs above or below the Ferron Sandstone Member due to the confinement of the coal bearing rocks beneath the Lower Blue Gate Shale Member and above the Tunuck Shale Member of the Mancos shale; both of these units have low permeabilities. On the other hand, the Blackhawk Formation is underlain by the Star Point Sandstone and overlain by the Castlegate Sandstone. Sandstones in these units can potentially serve as aquifers.

5.5 The Powder River Basin

The Powder River Basin is located in northeastern Wyoming and southern Montana (Figure 5-1). The basin covers an area of approximately 25,800 square miles, approximately 75% of which is within Wyoming. Fifty percent of the Powder River basin is believed to have the potential for coalbed methane production. Production volume was estimated at 147 billion cubic feet in 2000 (GTI, 2002).

Coalbeds in this region are interspersed at varying depths with sandstones and shale. The majority of the potentially productive coal zones range from 143 feet to 1,842 feet below ground (Randall, 1991). The uppermost formation is the Wasatch Formation, extending from land surface to 1,000 feet deep. Most of the coal seams in the Wasatch Formation are continuous and thin (six feet or less). The Fort Union Formation lies directly below the Wasatch Formation and can be as thick as 3,000 feet. The coalbeds in this formation are typically most abundant in the upper portion, named the Tongue River member. This member is typically 1,500 to 1,800 feet thick, of which up to a composite total of 350 feet of coal can be found in various seams. The thickest of the individual coal seams is over 150 feet thick. Recent estimates of coalbed methane reserves in the Powder River basin range from 7 to 40 trillion cubic feet (Montgomery, 1999; PRCMIC, 2000).

Coal beds in this basin are interspersed at varying depths with sandstones and shale. The Fort Union Formation that supplies municipal water to the city of Gillette is the same formation that contains the coals that are developed for coalbed methane. The coal beds contain and transmit more water than the sandstones. The sandstones and coal beds have both been used for the production of water and the production of coalbed methane. Total

Dissolved Solids levels in the water produced from coal beds meet the water quality criteria for USDWs.

EPA's understanding is that hydraulic fracturing currently is not widely used in this region due to concerns about the potential for increased ground water flow into the coalbed methane production wells and collapse of open hole wells in coal upon dewatering. According to the available literature, where hydraulic fracturing has been used, it has had little beneficial effect. Hydraulic fracturing has been done primarily with water, or gelled water and sand, although recorded use of a solution of potassium chloride (KCl) was identified in the literature.

5.6 The Central Appalachian Basin

The Central Appalachian Coal Basin is the middle basin of the three basins comprising the Appalachian Coal Region of the eastern United States, and includes parts of the states of Kentucky, Tennessee, Virginia, and West Virginia (Figure 5-1). It covers an area of approximately 23,000 square miles, with the highest potential for methane development in a small, 3,000 square mile area in southwest Virginia and south central West Virginia (Kelafant, et al., 1988).

The coal basin consists of six Pennsylvanian age coal groups (Zebrowitz et al., 1991, and Zuber, 1998). These coal groups typically occur as multiple coalbeds or seams that are widely distributed (Zuber, 1998). The coal seams, listed in order from oldest to youngest (West Virginia/Virginia name), are the Pocahontas No. 3, Pocahontas No. 4 (the Pocahontas coal seams include the Squire Jim and Nos. 1 to 7, but Nos. 3 and 4 are the thickest and most areally extensive), Fire Creek/Lower Horsepen, Beckley/War Creek, Sewell/Lower Seaboard, and Iager/Jawbone (Kelafant et al., 1988). The majority of the coalbed methane (2.7 trillion cubic feet) occurs in the Pocahontas seams (Kelafant et al., 1988). In southwest Virginia and south central West Virginia, target coal seams achieve their greatest thickness and occur at depths of about 1,000 to 2,000 feet (Kelafant et al., 1988).

The Nora Field in southwestern Virginia is one of the better known coalbed methane production fields, with over 250 coalbed methane wells drilled. Approximately 2,500 new coalbed methane wells were drilled last year within Buchanan County of southwestern Virginia (Wilson, 2001). The State of Virginia reportedly produced 72 billion cubic feet of coalbed methane in 2000 (Wilson, 2001). The Gas Technology Institute reports that basin-wide coalbed methane production stood at 52.9 billion cubic feet in 2000 (GTI, 2002).

Because most of the coal strata dip, a coalbed methane well's location within the basin may determine if hydraulic fracturing during the well's development will affect water quality within the surrounding USDW. For instance, on the northeastern side of the basin, the depth to the Pocahontas No. 3 coalbed is less than 500 feet. This depth gradually increases to over 2,000 feet farther westward across this portion of the basin, in the direction of dip of the coal seam. Therefore, a well tapping this coal seam in the eastern portion of the basin may be within a USDW, but a well tapping this coal seam in the western portion of the basin may be below the base of a USDW. Additionally, the base of the freshwater is not a flat surface, but rather an undulating one. These factors indicate that the relationship between a coalbed and a USDW must be determined on a site-specific basis.

Hydraulic fracturing is a common practice in this region. Foam and water are used as the fracturing fluids and sand serves as the proppant. Additives can include hydrochloric acid, scale inhibitors, and microbicides. Pocahontas Oil & Gas, a subsidiary of Consol Energy, Inc., invited EPA personnel to a well location where a hydraulic fracturing treatment was being performed by Halliburton Energy Services, Inc. Halliburton staff stated that typical fractures range in length from 300 to 600 feet from the well bore in either direction. However, fractures have been known to extend from as little as 150 feet to as much as 1,500 feet in length (Virginia Site Visit, 2001). According to the fracturing engineer on site, fracture widths range from one eighth of an inch to almost one and a half inches (Virginia Site Visit, 2001).

Since some coalbed methane exploration has moved to shallower seams, the Commonwealth of Virginia has instituted restrictions/regulation concerning depths at which hydraulic fracturing may be performed (Wilson, 2001). These restrictions require an operator to determine the elevation of the lowest topographic point and the elevation of the deepest water well within a 1,500-foot radius of any proposed extraction well. Hydraulic fracturing must occur at least 500 feet deeper than the lowest of these two points (Wilson, 2001).

5.7 The Northern Appalachian Basin

The Northern Appalachian Coal Basin is the northernmost of the three basins comprising the Appalachian Coal Region of the eastern United States. It includes parts of the states of Pennsylvania, West Virginia, Ohio, Kentucky, and Maryland (Figure 5-1). The basin lies completely within the Appalachian Plateau geomorphic province, covering an area of approximately 30,300 square miles. The Northern Appalachian basin trends northeast-southwest and the Rome Trough, a major graben structure, forms the southeastern and southern structural boundaries. The basin is bounded on the northeast, north, and west by outcropping Pennsylvanian aged sediments (Kelafant et al., 1988).

The six Pennsylvanian aged coal groups comprising the Northern Appalachian Coal Basin are the Brookville-Clarion, Kittanning, Freeport, Pittsburgh, Sewickley, and the Waynesburg. These coal groups are contained within the Pottsville, Allegheny, Conemaugh, and the Monongahela Groups (Kelafant et al., 1988). Coal seam depths range from surface outcrops to up to 2,000 feet below ground surface, with most coal occurring at depths shallower than 1,000 feet (Quarterly Review, 1993). These depth differences arise due to the dip of the coal beds. The total thickness of the Pennsylvanian-aged coal system averages 25 feet; however, better-developed seams within the coal groups can increase in thickness by up to twice the average (Quarterly Review, 1993).

Coalbed methane has been produced in commercial quantities from the Pittsburgh coalbed of the Northern Appalachian Coal Basin since 1932 (Lyons, 1997), after the discovery of the Big Run Field in Wetzel County, West Virginia, in 1905 (Hunt and Steele, 1991). As of 1993, O'Brien Methane Production, Inc. had at least 20 wells in southern Indiana County, Pennsylvania (Quarterly Review, 1993). Coalbed methane production development in the Northern Appalachian Basin has lagged, however, due to insufficient reservoir knowledge, inadequate well completion techniques, and coalbed methane ownership issues revolving around whether the gas is owned by the mineral owner or the oil and gas owner (Zebrowitz et al., 1991). Discharge of produced waters has also proven to be problematic (Lyons, 1997) for current and would-be coalbed methane field operators in the Northern Appalachian Coal Basin. Total coalbed methane production stood at 1.41 billion cubic feet in 2000 (GTI, 2002).

The Northern Appalachian Basin is situated in the Appalachian Plateaus physiographic province. The primary aquifer in this area is a Pennsylvanian sandstone aquifer underlain by limestone aquifers (USGS, 1984). Water quality data from eight historic Northern Appalachian Coal Basin projects show that estimated TDS levels ranged from 2,000 to 5,000 milligrams per liter at depths ranging from 500 to 1,025 feet below ground surface (Zebrowitz et al., 1991), well within the EPA's standard of 10,000 mg/L TDS for a USDW (40 CFR §144.3). Depths to the bottoms of the USDWs vary greatly in the basin, and are better determined on a site-specific basis.

Hydraulic fracturing fluids used in the Northern Appalachian Basin have included water and sand and nitrogen foam and sand (Hunt and Steele, 1991). The Christopher Coal Company/Spindler Wells Project, which took place from 1952 to 1959, stimulated one well with 12 quarts of nitroglycerin (Hunt and Steele, 1991). In the Vesta Mines Project of Washington County, Pennsylvania, the US Bureau of Mines used gelled water and sand to complete five wells in the Pittsburgh Seam (Hunt and Steele, 1991).

Because most of the coal strata dip, a well's location within a basin decides whether it is coincident with a USDW. For example, in the Pittsburgh Coal Group in Pennsylvania, the depth to the top of the coal group varies from outcrop to about 1,200 feet in the very southwestern corner of the state (Kelafant et al., 1988). The approximate depth to the bottom of the USDW is 450 feet. Therefore, production wells operating down to approximately 450 feet could potentially be hydraulically connected to the USDW.

5.8 The Western Interior Coal Region

The Western Interior Coal Region comprises three coal basins that include the Arkoma, the Cherokee, and the Forest City Basins, and encompasses the areas of six states: Arkansas, Oklahoma, Kansas, Missouri, Nebraska, and Iowa (Figure 5-1). The Arkoma Basin covers about 13,500 square miles in the states of Arkansas and Oklahoma. The Cherokee Basin is part of the Cherokee Platform Province, which covers approximately

26,500 square miles (Charpentier, 1995) in the states of Oklahoma, Kansas, and Missouri. The Forest City Basin covers about 47,000 square miles (Quarterly Review, 1993) in the states of Iowa, Kansas, Missouri, and Nebraska.

In the Arkoma Basin, major middle Pennsylvanian coalbeds occur within the Hartshorne, McAlester, Savanna, and Boggy Formations (Quarterly Review, 1993). The Hartshorne coals of the Hartshorne Formation are the most targeted for methane production in the Arkoma Basin, and range in depth from 600 to 2,300 feet in two productive areas of southeastern Oklahoma (Quarterly Review, 1993). In the Cherokee Basin, the coal seams primarily targeted by operators are the Riverton Coal of the Krebs Formation, and the Weir-Pittsburg and Mulky coals of the Cabaniss Formation (Quarterly Review, 1993). The Riverton and Wier-Pittsburg seams are about three to five feet thick and range in depth from 800 to 1,200 feet, while the Mulky Coal, which ranges up to two feet thick, occurs at depths of 600 to 1,000 feet (Quarterly Review, 1993). Individual coal seams within the Cherokee Group of the Forest City Basin range from a few inches to about four feet in thickness, with seams up to 6 feet in thickness (Brady, 2002; Smith, 2002). Depths to the top of the Cherokee Group coals range from approximately the surface to 230 feet below ground surface in the shallower portion of the basin in southeastern Iowa to about 1,220 feet in the deeper part of the basin in northeastern Kansas (Bostic et al., 1993).

As of March 2000, there were 377 coalbed methane wells in the Arkoma Basin of eastern Oklahoma, ranging in depth from 589 to 3,726 feet (Oklahoma Geological Survey website, 2001). The Arkoma basin contains an estimated 1.58 to 3.55 trillion cubic feet of gas reserves contained primarily in the Hartshorne coals (Quarterly Review, 1993). In the Cherokee Basin, unknown amounts of coalbed methane gas have been produced with conventional natural gas for over 50 years (Quarterly Review, 1993). Targeted coalbed methane production increased in the late 1980s, and at least 232 coalbed methane wells had been completed as of January 1993 (Quarterly Review, 1993). The Cherokee basin contains an estimated 1.38 million cubic feet of gas per square mile basin-wide (Stoeckinger, 1989) in the targeted Mulky, Weir-Pittsburg, and Riverton coal seams of the Cherokee Group (Quarterly Review, 1993). Nearly 10 trillion cubic feet of gas are located in eastern Kansas alone (PTTC, 1999). The Forest City Basin was relatively unexplored in 1993, with about ten coalbed wells concentrated in Atchison, Jefferson, Miami, Leavenworth, and Franklin Counties, Kansas (Quarterly Review, 1993). The Forest City Basin contains an estimated one trillion cubic feet of in-place gas (Nelson, 1999). For the entire region, coalbed methane production was 6.5 billion cubic feet in 2000 (GTI, 2002).

There are no currently productive aquifers within those portions of Oklahoma and Arkansas contained within the Arkoma Basin, only smaller alluvial aquifers bounding rivers. Water quality test results from the targeted Hartshorne seam in Oklahoma have shown the water to be highly saline (Quarterly Review, 1993). The base of fresh water in Arkansas is about 500 to 2,000 feet below ground surface (Cordova, 1963). However, Cordova (1963) does not define "fresh water." While the majority of the Cherokee Basin does not contain a principal aquifer, the Ozark and Douglas aquifers are contained within the basin (National Water Summary, 1984). The confined Ozark aquifer, composed of weathered and sandy dolomites, typically contains water wells that extend from 500 to 1,800 feet in depth (National Water Summary, 1984). The usually unconfined Douglas aquifer is a sandstone channel of the Pennsylvanian age (National Water Summary, 1984). Wells are usually five to 400 feet deep in this aquifer. In Kansas, depth to the base of the Ozark aquifer is roughly 1,750 feet below ground surface (Ozark Aquifer Base Map, 2001). In Oklahoma, the Cherokee Basin also contains the Garber-Wellington and Vamoosa-Ada aquifers (National Water Summary, 1984). Well depths in these two aquifers usually range from 100 to 900 feet in depth (National Water Summary, 1984). The Forest City Basin contains the Jordan aquifer, the Dakota aquifer, glacial drift, alluvial, and Paleozoic-aged rock aquifers. Wells in these aquifers commonly range in depth from 300 to 2,000 feet, 100 to 600 feet, 30 to 200 feet, 10 to 150 feet, and 30 to 2,200 feet in depth, respectively (National Water Summary, 1984). Throughout the Western Interior Coal Region, water quality sampling has shown TDS levels to range from 500 to 40,000 mg/L TDS (Missouri Division of Geological Survey and Water Resources, 1967).

Hydraulic fracturing is a common practice in the Western Interior Coal Basin. Hydraulic fracturing fluids such as linear gel, acid and nitrogen foam were used extensively in the Western Interior coal region before 1992, and slick water treatments became common in 1993. Hydraulic fracturing is still practiced in the basin.

Based on depths to the Hartshorne Coal (0 to 4,500 feet in Arkansas) and the base of fresh water (500 to 2,000 feet in Arkansas), it appears that coalbed methane extraction wells in the Arkoma Basin could be coincident with potential USDWs in Arkansas (Andrews et al., 1998; Cordova, 1963). Based on maps provided by the Oklahoma Corporation Commission (2001) as to the depths of the 10,000 mg/L of TDS ground water quality boundary in Oklahoma, the location of coalbed methane wells and USDWs would most likely not coincide in Oklahoma. This is based on depths to coals typically greater than 1,000 feet (Andrews et al, 1998) and depths to the base of the USDW typically shallower than 900 feet (OCC Depth to Base of Treatable Water Map Series, 2001).

In the Cherokee Basin, co-location of coalbed methane wells targeting the Cherokee Group coals in Kansas and USDWs exists. Depths to the top of coalbeds range from 800 to 1,200 feet (Quarterly Review, 1993) while the depth to the base of freshwater is estimated at 1,750 feet (Mapped information from the Kansas Data Access and Support Center, 2001). More information concerning water quality is required prior to any determination of coalbed methane well/USDW co-location in Missouri. However, current levels of coalbed methane activity are minimal in the state. In addition, since only a very small portion of the Cherokee Basin falls within the state, this portion of the basin needs to be delineated more precisely to see which USDWs are contained within this small part of the basin. Lastly, in the Forest City Basin, there appears to be little relationship between water supplies and coalbeds that may be used for coalbed methane extraction. However, aquifer and well information from the National Water Summary (1984) indicates that a co-location of the two could exist in Iowa and Nebraska. More information is needed to define the relationship between coalbeds and USDWs in the Forest City Basin.

5.9 The Raton Basin

The Raton basin covers an area of about 2,200 square miles in southeastern Colorado and Northeastern New Mexico (Figure 5-1). It is the southernmost of several major coal-bearing basins along the eastern margin of the Rocky Mountains. The basin extends 80 miles north to south and as much as 50 miles east to west (Stevens et al., 1992). It is an elongate asymmetric syncline, 20,000 to 25,000 feet thick in the deepest part.

There are two major coal formations in the Raton Basin, the Vermejo and the Raton. The Vermejo coals range in thickness from five to 35 feet while the Raton coal layers span a 10 to 140-foot thickness range. Although the Raton Formation is much thicker and contains more coal than the Vermejo Formation, individual coal seams are less continuous and are generally thin and lenticular.

Methane resources for the basin have been estimated at approximately 10.2 trillion cubic feet contained in the Vermejo and Raton Formations (Stevens et al., 1992). As of 1992, about 114 coalbed methane exploration wells had been drilled in the basin (Quarterly Review, 1993). It was reported recently that the average coalbed methane production rate of wells in the Raton Basin was close to 300 thousand cubic feet per day, and annual production in 2000 was 30.8 billion cubic feet (GTI, 2002).

The coal seams of the Vermejo and Raton Formations developed for methane production also contain water that meets the water quality criteria for a USDW. The underlying Trinidad Sandstone and other sandstone beds within the Vermejo and Raton Formations, as well as intrusive dikes and sills, also contain water of sufficient quality to meet the USDW water quality criteria.

Coalbed methane well stimulation using hydraulic fracturing techniques is a common practice in the Raton Basin. Records show that fracturing fluids used are typically gels and water with sand proppants. Hemborg (1998) showed that in most cases water yield decreased dramatically as methane production continued over time. However, some wells exhibited increased water production as methane production continued or increased over time. Two causal factors were suggested (Hemborg, 1998) for the rise in water production:

1. Well stimulation had increased the zone of capture of the well to include adjacent water-bearing sills or sandstones that were hydraulically connected to recharge areas, or,

2. Well stimulation had created a connection between the coal seams and the underlying water-bearing Trinidad Sandstone. This is most likely due to fractures extending from the coal layers into adjacent sandstone aquifers.

5.10 The Sand Wash Basin

The Sand Wash Basin is located in northwestern Colorado and southwestern Wyoming. It is part of the Greater Green River Coal Region that also includes the Washakie Basin, the Great Divide (Red Desert) Basin, and the Green River Basin (Figure 5-1). These sub-basins are separated by uplifts caused by deformation of the basement rock. For example, the Sand Wash Basin is separated from the adjacent Washakie Basin by the Cherokee Arch, an anticline ridge that runs east to west along the Colorado-Wyoming border. The Greater Green River Coal Region, in total, covers an area of approximately 21,000 square miles. The Sand Wash Basin covers approximately 5,600 square miles, primarily in Moffat and Routt Counties of Colorado.

The coal bearing formations in the region include the Williams Fork, the Fort Union, and the Wasatch Formations. The total thickness of the coal seams encountered in these formations can be up to 150 feet (Quarterly Review, 1993). Of all the formations, the Williams Fork is the most significant coal-bearing unit because it has the thickest and most extensive coal seams. Coal bearing strata are 5,000 feet deep along western portions of the basin and outcrop along the southern and eastern margins of the basin. The coal seams are interbedded with sandstones and shale. The thickest total coal deposits in the Williams Fork Formation, up to 129 feet, are centered on Craig, Colorado. These deposits are composed of several separate seams up to 25 feet thick interspersed between layers of sedimentary rock.

Coalbed methane resources in the Sand Wash Basin have been estimated at 101 trillion cubic feet. Approximately 90% of this is within the Williams Fork Formation. Approximately 24 trillion cubic feet of coalbed methane are located at depths less than 6,000 feet below grade (Kaiser et al., 1994a). Some investigation and very limited commercial development of this resource have occurred, mostly in the late 1980s and early 1990s. Records from the Colorado Oil and Gas Commission indicate that approximately 31 billion cubic feet of coalbed methane was produced in Moffat County during 1995 (Colorado Oil and Gas Conservation Commission web site, 2001). There appears to be no commercial production at present. Development of coalbed methane resources in the Sand Wash Basin has been slower than in many other areas due to limited economic viability. The need for extensive dewatering in most wells has been a limiting factor, compounded by relatively low coalbed methane recovery. In recent years, permits for new gas wells have been issued indicating that there may be some continued interest in this area (Colorado GIS, 2001). There appears to be no commercial production at present (GTI website, 2002).

Kaiser and Scott (1994) summarize their extensive investigation of ground water movement within the Fort Union and Mesaverde group. The Mesaverde group is a highly transmissive aquifer. The coal seams within the group may be the most permeable part of the aquifer. Lateral flow within the Fort Union Formation is slower. Ground water quality in the basin varies greatly. Typically, chloride and TDS concentrations within the coal bearing Mesaverde group are low and potentially within potable ranges in the eastern portion of the basin, implying existence of a USDW. TDS concentrations increase as the water migrates toward the central and western margins of the basin. TDS concentrations have been detected in the western portion of the basin at levels significantly higher than USDW ranges.

The use of fracturing fluids, specifically water and sand proppant, has been reported for this basin. No record of any other fracturing fluid types has been located.

Although variable, the water quality within the fractured coals indicates the presence of USDW-quality water within the coal seams (Scott and Kaiser, 1994. More data need to be gathered in order to make more definitive conclusions about USDW contamination pathways.

5.11 The Washington Coal Regions (Pacific and Central)

The Pacific Coal Region (Figure 5-1) is approximately 6,500 square miles and lies along the western flank of the Cascade Range from Canada into northern Oregon within the Puget downwarp structure. Bellingham, Seattle, Tacoma, Olympia and Portland lie in or adjacent to the basin. The Central Coal Region (Figure 5-1) primarily lies within the Columbia Plateau, between the Cascade Range to the west and the Rocky Mountains to the east, in Idaho. This region extends from the Okanogan highlands to the north to the Blue Mountains to the south, and encompasses approximately 63,320 square miles.

The coal bearing deposits of the Pacific and the Central Coal Regions are Cretaceous to Eocene age and formed within fluvial and deltaic depositional environments prior to the uplift of the Cascade Mountain Range. The thick coalbeds of the Pacific and Central Basins are thought to represent peat accumulations in poorly drained swamps of the lower deltas while the thinner coalbeds probably formed in the better drained upper deltas (Buckovic, 1979 as cited by Choate et al., 1980). The complex stratigraphy and structural deformation of the coals of the Pacific Coal Region are major obstacles to exploration and development of gas fields. Although the coals of the Central Coal Region may not be as greatly deformed and unpredictable as those in the Pacific Coal Region, they are obscured by the Columbia River Basalt Group, in which individual basalt flows up to 300 feet thick can cover thousands of square miles.

The occurrence of methane in ground water is one factor leading to the identification of the gas potential in Washington. Methane in ground water occurs in the basalts, but only in confined aquifers (porous or fractured zones near the top or bottom of a basalt layer), and is thought to have migrated upward from underlying coalbeds. Choate et al. (1980) estimated coalbed methane resources for four target sub-basins representing 1,800 square miles of the Pacific Coal Region to be 0.3 to 24 trillion cubic feet. Methane had been encountered in 67 oil and gas exploration wells drilled in this region by 1984. Gas was found at depths of less than 500 feet in 25 wells, less than 1,000 feet in 38 wells, and less than 2,000 feet in 50 wells. Pappajohn and Mitchell (1991) estimated the coalbed methane potential of the Central Coal Region to be more than 18 billion cubic feet per square mile. The operation of the Rattlesnake Hills gas field between 1913 and 1941 in the western part of the Central Coal region indicates that greater potential for development may exist. According to the available literature, there were no producing fields in either the Pacific Coal Region or the Central Coal Region in Washington as of 2000 (GTI, 2001).

Water supply wells and irrigation wells in the Columbia River Basalts and water wells in numerous different lithologies in the Pacific Coal Region have been recognized as containing methane. Data demonstrating the co-location of a coal seam and a USDW was found for Pierce County, where methane gas test well results report TDS levels far less than the 10,000 mg/L USDW water quality threshold (Dion, 1984). These aquifers can be classified as USDWs. Data demonstrating the co-location of a coal seam and a USDW was found for Pierce County, where methane gas test well results report TDS levels of 1,330 to 1,660 mg/L, which is far less than the USDW classification limit of 10,000 mg/L (Dion, 1984). Development of methane in the Central Coal region may have some impact on highly productive basalt aquifers that are already in use as large sources of irrigation water for agriculture (Dion, 1984).

Hydraulic fracturing of coalbed methane wells using sand and nitrogen foam treatments has been documented (Quarterly Review, 1993). However, optimal stimulation and completion methods for use in the structurally difficult Pacific gas region are yet to be applied and proven.

Data demonstrating the co-location of a coal seam and a USDW was found for Pierce County, where methane gas test well results report TDS levels of 1,330 to 1,660 mg/L, which is far less than the USDW classification limit of 10,000 mg/L (Dion, 1984).

5.12 Summary

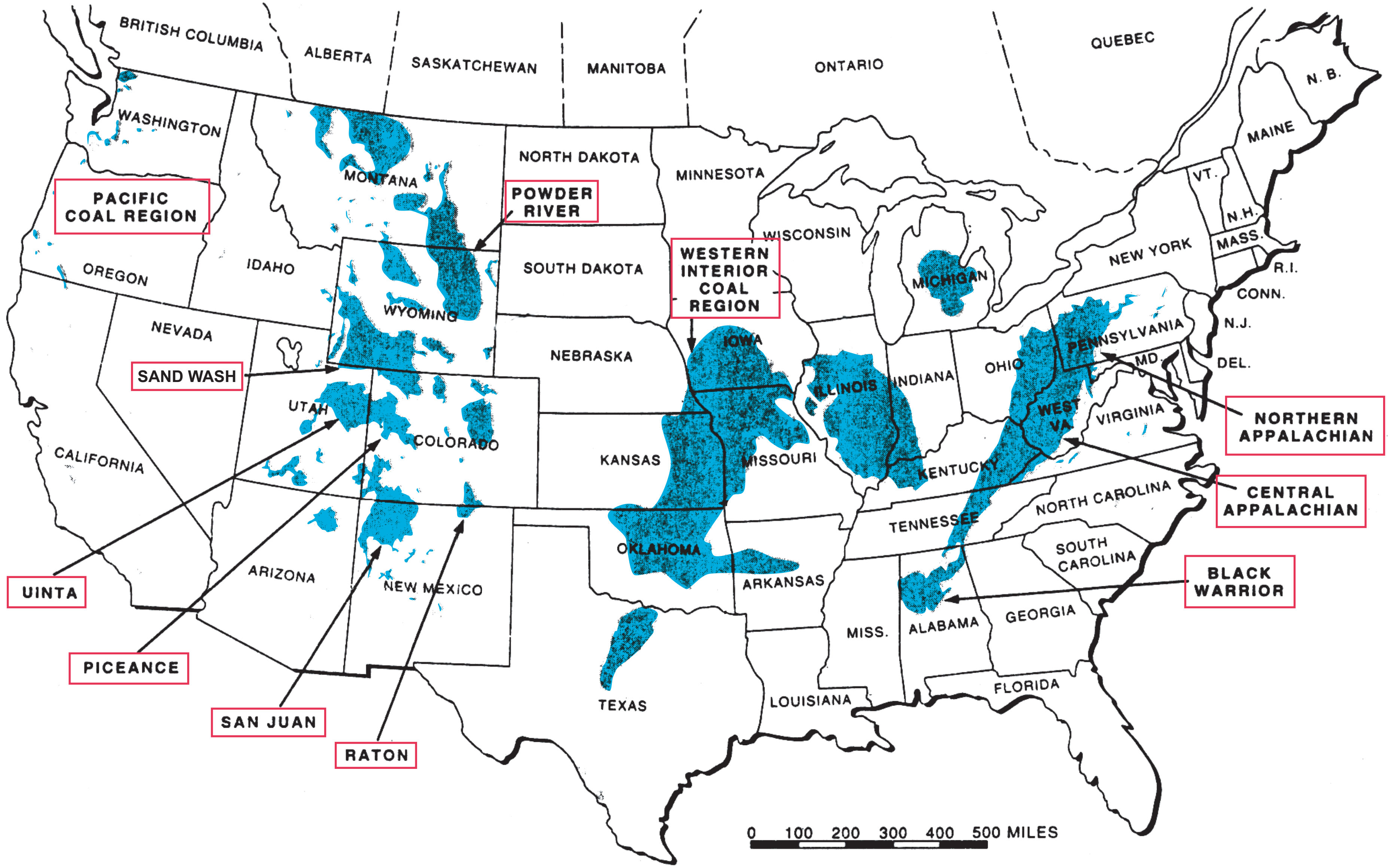
Ten of the eleven major coal basins in the U.S. are definitely or likely located wholly or partially within USDWs. The literature also indicates the possibility that hydraulic fracturing may create communication between coalbed formations and adjacent aquifers in four of the basins: the Uinta, Powder River, Raton, and Washington basins. Hydraulic fracturing of coalbed methane production wells has been documented in each Basin, although it is not currently practiced in the Powder River Basin.

Table 5-1. Evidence In Support Of Coal-USDW Co-Location In U.S. Coal Basins

Basin	Is coal found within the USDW?	Explanation and/or evidence
San Juan	Yes	A large area of the Fruitland system produces water containing less than 10,000 mg/L TDS, the water quality criteria for a USDW. Analyses taken from a selected coal well area show that the majority of wells (16 of 27 wells) produce water containing less than 10,000 mg/L TDS (Kaiser et al., 1994).
Black Warrior	Yes	Almost all waters of the Pottsville aquifer contain less than 10,000 mg/L TDS, and most waters in the Pottsville flow systems contain less than 3,000 mg/L TDS, even within the deeper, methane-target coal seams such as the Mary Lee beds (Pashin et al., 1991; Pashin and Hinkle, 1997). In the early 1990's, several authors reported fresh water production from coalbed wells at rates up to 30 gallons per minute (summarized in Pashin et al., 1991; Ellard et al., 1992).
Piceance	Unlikely	The stratigraphic separation between the coal gas bearing zone and the lower aquifer system in the Green River Formation is approximately 6,400 feet. The major coalbed methane target, the Cameo-Wheeler-Fairfield coal zone lies roughly 6,000 feet below the ground surface in a large portion of the basin (Tyler et al., 1998). A composite water quality sample taken from 4,637 to 5,430 feet deep within the Cameo Coal Group in the Williams Fork Formation exhibited a TDS level of 15,500 mg/L (Graham, CDWR, personal communication 2001). The produced water from coalbed methane extraction in the Piceance Basin is of such low quality that it must be disposed of in evaporation ponds or re-injected into the formation from which it came, or at even greater depths (Tessin, 2001).
Uinta	Likely	Production waters from coal seams at the higher elevation Castlegate Field within the Blackhawk Formation appear to have TDS levels of about 5,000 mg/L (Quarterly Review, 1993).
Powder River	Yes	A report prepared by the US Geological Survey showed that samples of water co-produced from 47 CBM wells in the Powder River Basin all had a TDS of less than 10,000 mg/L (Rice et al., 2000). The water produced by coalbed methane wells in the Powder River Coal Field commonly meets drinking water standards. In fact, production waters such as these have been proposed as a separate or supplemental source for municipal drinking water in some areas (DeBruin et al., 2000).
Central Appalachian	Likely	Depths of coal groups are coincident with fresh water in at least two of the states within the overall basin (Kelafant et al., 1988; Wilson, 2001; Foster, 1980; Hopkins, 1966 and USGS, 1973). Anecdotal information suggests that private wells in Virginia are screened within coal seams (Wilson, VDMME, 2001).
Northern Appalachian	Yes	The depth of each coal group within the basin is coincident with the depths of USDWs (Kelafant et al., 1988; Platt, 2001; Foster, 1980; Hopkins, 1996; USGS, 1973; Sedam and Stein, 1970; USGS, 1971; Duigon, 1985). Water quality data from eight historic Northern Appalachian Coal Basin projects show that TDS levels were below 10,000 mg/L (Zebrowitz et al., 1991).

Table 5-1. Continued

Basin	Is coal found within the USDW?	Explanation and/or evidence
Western Interior		
Arkoma	Yes (in Arkansas) Unlikely (in Oklahoma)	The depths of coal beds within the State of Arkansas are coincident with depths to fresh water (Andrews et al., 1998; Cordova, 1963; Friedman, 1982; Quarterly Review, 1993). Based on maps provided by the Oklahoma Corporation Commission (2001) as to the depths of the 10,000 mg/L of TDS ground water quality boundary in Oklahoma, the location of coalbed methane wells and USDWs would most likely not coincide in Oklahoma. This is based on depths to coals typically greater than 1,000 feet (Andrews et al, 1998) and depths to the base of the USDW typically shallower than 900 feet (OCC Depth to Base of Treatable Water Map Series, 2001).
Cherokee	Yes	The depths of coal beds within the State of Kansas are coincident with depths to fresh water (Quarterly Review, 1993; McFarland, 2001; DASC, 2000).
Forest City	Unlikely	The shallow thickness of the aquifer suggests that there is significant separation from the deeper coalbeds within the basin (Bostic et al, 1993; DASC, 2001; Condra and Reed, 1959; Flowerday et al., 1998).
Raton	Yes	Water quality results from coalbed methane wells in the Raton Basin demonstrate TDS content of less than 10,000 mg/L. Nearly all wells surveyed show a TDS of less than 2,500 mg/L, and more than half had TDS of less than 1,000 mg/L (National Water Summary, 1984).
Sand Wash	Yes	Two gas companies produced water from coals that showed TDS levels below 10,000 mg/L. At Craig Dome in Moffat County, Cockrell Oil Corporation drilled 16 coalbed methane wells. The wells yielded large volumes of fresh water with TDS <1,000 mg/L (Colorado Oil and Gas Commission web site, 2001). Fuelco was operating 11 wells along Cherokee arch. Water pumped from the wells contained 1,800 mg/L of TDS and was discharged to the ground with a NPDES permit (Quarterly Review, 1993).
Washington	Yes	Data demonstrating the co-location of a coal seam and a USDW was found for Pierce County. Water quality information from four gas test wells indicates TDS levels between 1330 and 1660 mg/L, well below 10,000 mg/L (Dion, 1984). Wells in the Basalts commonly yield 150 to 3,000 gallons per minute. Total dissolved solids in the water produced generally range from 250 to 500 mg/L (Dion, 1984).



Locus Map of Major U.S. Coal Basins
(Quarterly Review, Methane From Coal Seams Technology, 1993)

1027/reports/ch5/fig-5-1.eps	Figure 5-1